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Technical Report

LABORATORY TEST REQUIREMENTS FOR MARINE SHOCK ISOLATION SEATS

by

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SYMBOLS, ABBREVIATIONS, AND ACRONYMS

A/D .... analog-to-digital
ASCII .... American Standard Code for Information Interchange
ATD .... Anthropomorphic test device
dB .... decibel
dc .... direct current
ft .... feet
g .... acceleration due to gravity
HSC .... high sped craft
Hz .... Hertz (cycles per second)
kg .... kilogram
m .... meters
MEMS .... micro electro-mechanical systems
MR .... mitigation ratio
msec or ms .... millisecond
mV .... millivolt
s/s .... samples per second
sec .... second
SDOF .... single degree-of-freedom
SRS .... shock response spectrum
SRS_S .... shock response spectrum of seat cushion acceleration
SRS_B .... shock response spectrum of seat base input acceleration
x, y, z .... coordinate axes

ADMINISTRATIVE INFORMATION

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SUMMARY

This report provides preliminary guidance for laboratory testing of marine shock isolation seats. The purpose of the test is to demonstrate the effectiveness of a passive seat in reducing simulated wave impact loads in a laboratory before installation in a high-speed planing craft. It includes testing procedures, instrumentation system guidance, data processing requirements, test criteria, and test report contents. This guide presents a collection of best practices, preferences, and expectations that will be updated as new criteria or techniques are developed.

INTRODUCTION

Background

Small craft that operate at high-speeds in rough seas subject the crew and passengers to wave impacts that may cause extreme discomfort. Craft designers therefore often include shock isolation seats to mitigate these negative effects. Current design practice is to install seats that employ springs and dampers (i.e., shock absorber) or leaf-spring assemblies as protection mechanisms. They are referred to as passive seats because the spring-damper assembly responds to individual wave impacts with no active elements that change real-time to adapt to the environment.

Spring-damper assemblies are also employed as protection mechanisms on land vehicles (e.g., tractors, trucks, automobiles, buses) and onboard larger ships for mine blast protection. Experience has demonstrated that dynamic environments are different, and that seats designed for land vehicle or mine blast applications may not protect against the unique characteristics of wave impacts on small high-speed craft. Seats have been installed in craft only to find out during subsequent seakeeping trials that they provide little to no protection or amplify base input motions. There is therefore a need to provide guidance on how to simulate these unique wave impacts in a laboratory test that will demonstrate the mitigation performance of passive shock isolation seats prior to installation in a high-speed craft.

High-speed craft motions include all six degrees of freedom: three translational (i.e., heave, surge, sway) and three rotational (i.e., pitch, roll, and yaw). During severe wave impacts in head seas the largest accelerations are in the vertical (i.e., heave) direction, but the other response degrees of freedom are just as important for people. Feedback from personal experiences indicates that any force out of plane with the vertical axis of standing or sitting that induces body torque or bending can be just as punishing as the vertical shock input. Simulation of fore-aft accelerations during a laboratory test is recommended herein as a test option achieved by an angle insert below the seat. Specific guidance for required off-axis testing (i.e., not just vertical testing) will be included in future revisions as data becomes available.

Scope

This guide is applicable to shock isolation seats used in high-speed planing craft. The test criteria presented herein are intended for craft ranging from 7-meter to 30-meter planing craft. The test procedures are intended only for passive seats with no active sensors or mechanisms for real-time adaptation to the dynamic environment, and no use of the occupants' legs to mitigate an impact. In addition to protection mechanisms, shock isolation seats universally offer ergonomic features that provide differing degrees of comfort. This test standard addresses only the protection characteristics of seats; seat ergonomics is not addressed.

Normative References

The following references, in whole or in part, provide supplemental information deemed important for successful implementation of the test procedures and performance metrics presented in this guide. Additional relevant information is provided in the list of references.

ISO 18431-4 (2006E): *Mechanical vibration and shock – Signal Processing – Part 4: Shock-response spectrum analysis,* International Organization for Standardization, Geneva, Switzerland, 2006.

ANSI/ASA S2.62-2009: *Shock Test Requirements for Equipment in a Rugged Shock Environment*, American National Standards Institute and Acoustical Society of America, Melville, N.Y., 2009.

Testing and Evaluation of Life-Saving Appliances, Maritime Safety Committee Resolution MSC.81(70), Life-Saving Appliances, 2003 Edition, International Maritime Organization, 2003.

Terms and Definitions

Acceleration due to gravity. 9.80665 m/sec^2, 32.174 ft/sec^2

Peak acceleration. The peak acceleration is the largest instantaneous acceleration (i.e., rate-of-change of velocity) of recorded motions during a transient event.

Response mode decomposition. The mathematical separation of a recorded transient response into its different relevant modes of response is referred to as response mode decomposition. The modes of response typically recorded in small craft acceleration data or laboratory test data are rigid body modes and structural vibration modes.

Payload. The payload is the additional weight of an inert mass added to the seat assembly to simulate the weight of a human occupant sitting on the seat (with or without carried equipment).

Rigid body motion. Rigid body motions are the absolute translations (heave, surge, and sway) and rotations of the test platform that may occur in all three axes during a test. Low-pass filtering of acceleration data is a response mode decomposition process used to estimate rigid body acceleration. The impulsive load of a wave impact can be quantified by the amplitude and duration of the rigid body acceleration at the base of a seat during an impact.

Seat base. The seat base is the point or points of attachment between the seat assembly and the test platform assembly. In a laboratory test it is the simulated deck of a craft.

Seat cushion. The layer or layers of padding material added to an otherwise hard seat assembly for support, comfort and style. The cushion is sometimes referred to as the seat pad.

Seat pan. The seat pan is the hard structure above the spring-damper assembly that supports the seat cushion.

Shock. The term shock is used to imply mechanical shock, as opposed to electrical shock or chemical shock. Mechanical shock is a transient excitation of a physical system that is characterized by suddenness and severity. The acceleration recorded during a severe wave slam or laboratory test is referred to as a shock pulse.

Test platform. The test platform is the rigid structural assembly to which the test seat is attached.

TEST DESCRIPTION

Test Seat

The test seat should be a production-line seat or one that suitably represents seats installed in operating craft. A description of the test seat should be provided that includes physical characteristics such as dimensions, key subassembly parts (e.g., arm rests or foot- rests), cushions and padding, weights, etc., and normal operational characteristics such as adjustment options. The test seat should be attached to the test platform as it would be attached to the deck of a craft. Seats with manual adjustments for occupant weight, or shock absorber damping should be tested in adjustment settings as if an occupant of the specified payload weight where sitting in the seat.

Payload

The seat payload should be an inert mass secured to the seat cushion using ratchet-type straps to simulate the mass of a human occupant securely fastened with seat belts and/or harness straps. The straps should be positioned to place the center of the payload mass as close as possible to the vertical axis of the motion of the spring-damper assembly. For production-line seats without seat belts or harnesses, the inert mass should be secured by straps that allow approximately 2.5 centimeters (1 inch) of free vertical movement while keeping the center of mass approximately aligned. Straps in horizontal and vertical orientations should be used to prevent the payload from significant rotation or coming adrift during or after each test. Inert masses may include anthropomorphic test devices (ATD) or molded forms to simulate the human buttocks shape if specified. Otherwise, ballast bags or ballast weights may be used as payload.

> *Tip: If ballast bags filled with sand are employed it is recommended that several individual tightly-packed bags (e.g., 11.5 kg bags) be placed inside a larger ballast bag (i.e., material made from laminated or coated fabric) with the ballast bag secured to the seat.*

At least three different payload weights should be tested that correspond to the 95th, 50th, and 5th percentile weights of the intended male user population. Seats designated for craft

intended for male and female populations should be tested with 95th and 50th percentile male population payload weights, and a third weight equal to the 5th percentile female population weight.

Tip: Testing three different payload weights is important. There is currently insufficient evidence for different types of seats to suggest that full protection for the upper, mean, and lower range of occupant weights can be verified by one or two test payloads. As more evidence becomes available it may be reasonable to reduce the number of payload weights to be tested.

The payload weight may include the additional weight of occupant carried equipment if specified. Payload descriptions, weights, and securing mechanisms should be reported. Appendix A provides guidance for payload weights in the absence of payload specifications. Figure 1 shows example tests of shock isolation seats that used steel plates as payload weight (right side photograph) and an ATD (left side photograph) [1][1].

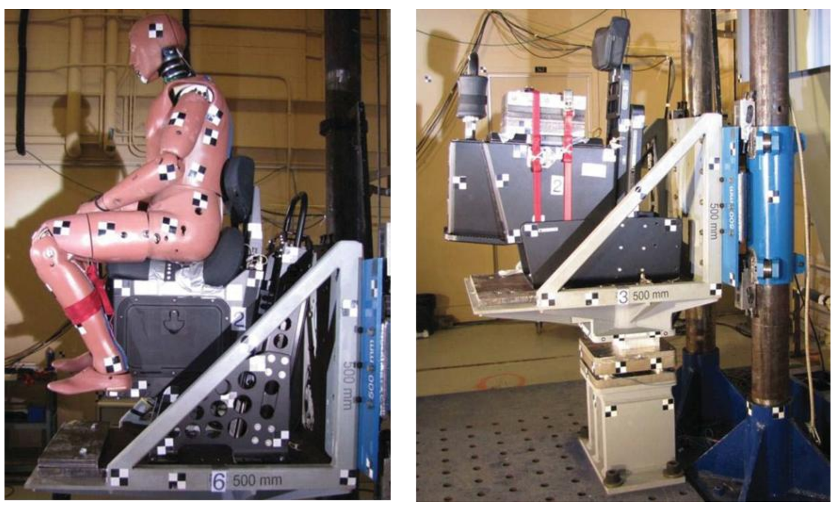

Figure 1. Anthropomorphic test device (ATD) and steel plate payload weights [2].

Tip: The use of ATDs as seat payload is desirable, but testing three with different weights may be cost prohibitive. The current preference is to assess seat performance over a range of weights. If one or two ATDs are available ballast weight may be added to the ATD to achieve the desired range of weights, otherwise ballast bags or ballast plates may be used.

[1] Numbers in brackets are references listed at the end of this guide
[2] Photograph provided courtesy of Defense Research and Development Canada Atlantic

Protection and Operability Requirements

Protection and operability requirements determine if the test seat meets the specified severity threshold after each test. Both the protection and failure criteria should be specified, including requirements for pre- and post-test operational assessment. The failure criteria should include those listed below.

Operability Requirements.

Following each test the seat should maintain all operational movement and adjustment capabilities, including unimpeded vertical motion of spring-damper assemblies or leaf-springs without binding or stoppage, proper operation of manual adjustments including foot-rest adjustments, or other operational features.

Protection Requirements.

The seat mitigation ratio (MR) is the measure of seat performance. It is the severity of the seat response motion divided by the severity of the base input motion, as given by equation (1).

$$\text{Mitigation Ratio (MR)} = \frac{\text{Seat Response Severity}}{\text{Base Input Severity}} \qquad \text{Equation (1)}$$

Mitigation is achieved when the MR value is less than one. A ratio equal to one indicates no mitigation was achieved, and a value greater than one indicates the mechanism amplified the deck input severity. Appendix B presents the method for computing the seat response severity and base input severity to be used in equation (1). Acceleration data processing guidance is provided later in the report.

Failure Criteria

Seat failure criteria should include the following:

a. Seat structural damage

b. Components adrift that could be a safety hazard to personnel

c. Seat operability malfunction

d. MR $\geq$ 1.0 See equation (1).

Test Method

Drop Test Method

The seat and payload should be installed on a rigid platform that is dropped from a height to achieve the desired impact severity. Figure 1 showed an example laboratory drop test fixture. The impact surface must be able to deflect or deform to produce the desired impact pulse shape, amplitude, and duration. The duration of the pulse must be relatively long to simulate the unique character of wave impacts. Figure 2 presents another drop test method for simulating the long duration pulse of a wave impact. A rigid wedge attached to the bottom of the platform impacts the sand. The wedge acts as a pulse shaper that can achieve the desired pulse shape, duration and peak acceleration [2]. Appendix C describes the wedge fixture.

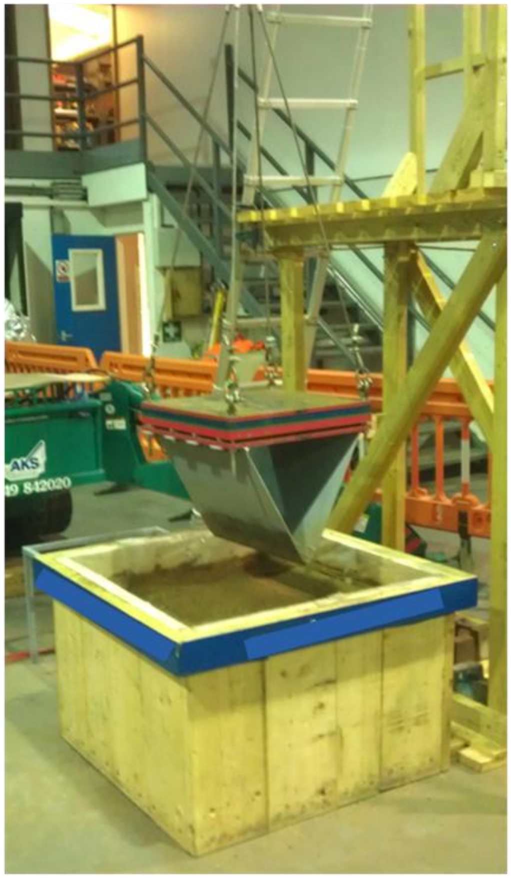

Figure 2. Wedge drop test for simulating wave impact pulse[3]

Alternative Methods

Test methods other than a drop test method may be employed to test passive seats if the method achieves the required test severity thresholds presented later in this report.

Coordinate Axes

Vertical motion upward is in the positive z direction. The orthogonal x and y directions define the plane of the horizontal test platform and the plane of the seat pan with positive x pointed in the direction of sight by a hypothetical seat occupant. Figure 3 shows example x, y, and z coordinates for a generic shock isolation seat assembly. Location 1 denotes motion below the spring-damper assembly at the base of the seat. Location 2 denotes motion above the spring-damper assembly on the seat pan, and Location 3 denotes motion on the seat cushion.

[3] United Kingdom Crown copyright photograph with permission

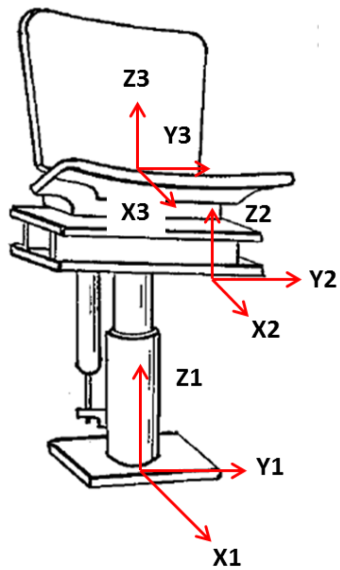

Figure 3. Seat motion coordinates

Angled Drop Test

Testing seats with an angle insert is optional. Wave impact loads in the transverse x and y directions also occur during operations in rough seas depending upon craft pitch, roll, craft heading, speed, and the location of hull impact on a wave (e.g., leading flank, wave crest, or following flank). This can be simulated by using an angle insert between the test platform and the base of the seat [3]. If specified, impact angles with the axis of the seat rotated aft (i.e., minus x direction) 10 degrees and 20 degrees should be tested.

INSTRUMENTATION

General Requirements.

Data Utilization

Instrumentation is required for all seat tests prescribed by this guide. Motion at the base of the seat is measured at a rigid location on the test platform to verify that the required impact severity threshold has been achieved. Motion of the seat above the spring-damper assembly is measured and compared to the motion of the seat base to assess the effectiveness of the seat assembly in reducing the impact severity.

Bandwidth

The presumption that motions data has been acquired properly cannot be overstated, because improperly collected data will result in meaningless analysis results. Attention must be paid to sensor mounting, powering, and signal conditioning [4 – 8]. Appropriate anti-aliasing filtering must also be applied as part of the analog-to-digital (A/D) conversion process. Digital data acquisition requires the signal to be band limited to preclude aliased frequency components in the data signal. Sufficient information for evaluating seat mitigation effectiveness can be achieved with a data bandwidth of dc to 100 Hz.

Measurement Parameter

Acceleration is the variable for measurement that defines the severity of the shock input motion at the base of the seat. Acceleration is also the variable for measuring the severity of the response motion measured on the seat above the spring-damper assembly.

> Tip: Measuring the relative displacement across the spring-damper assembly is optional but can be helpful for evaluating excursion space limits during higher severity impacts.

Data Acquisition System

Analog-to-Digital Conversion

Modern digital data acquisition and measurement systems are self-contained (i.e., they do not need an external computer), relatively inexpensive, highly reliable, and available from a number of sources. Nearly all equipment has a minimum of 16-bit A/D conversion with consequent signal resolution of 65,536 parts (98 dB signal/noise), and many manufacturers offer 24-bit A/D systems. For laboratory drop tests of seats, a data acquisition system should have a minimum of 16-bit A/D, and provisions for assuring alias signal rejection through fixed low-pass hardware pre-filters, oversampling, or a combination of both. A resolution of better than 0.001 g is achievable for a 25-g accelerometer coupled with a 16-bit data acquisition system.

Sampling Rate

The minimum sampling rate should be 512 samples per second (s/s).

> Tip: Most data acquisition systems are capable of sample rates per channel in the range of 100,000 samples per second or greater. Sampling at 512 s/s or greater is easily achievable.

Anti-Alias Filter

A pre-filter should be employed in the hardware prior to A/D conversion to prevent alias frequencies in the data. A 100-Hz low-pass filter with characteristics similar to a 4-pole Butterworth filter is suggested.

Data Storage

Data may be stored in a binary form as a matter of efficiency, but is should be converted to a human-readable ASCII (American Standard Code for Information Interchange) format.

> Tip: Data saved in ASCII format can be easily reviewed using text editor software like Microsoft®'s Notepad and Wordpad, or can be opened using spreadsheet software like Microsoft®'s Excel. Likewise, ASCII data can be analyzed using engineering software like DADiSP®, MATLAB®, or LabVIEW™, for example.

Sensors

Accelerometers

Piezoresistive, servo, or micro electro-mechanical systems (MEMS) type accelerometers should be used because they have dc response (i.e., the ability to operate over a frequency range beginning at zero Hz) that can measure -1g during the free-fall phase. They should have a minimum frequency response of dc to 1,000 Hz, a nominal full-scale range of ± 25 g, and a nominal sensitivity of 50 mV/g or greater.

> Tip: Perhaps the most popular, economical, and widely available are MEMS accelerometers, with prices in the range of a few hundreds of dollars each.

> Tip: Piezoelectric accelerometers should not be used because they have a lower frequency limit greater than zero Hz.

Sensor Positioning

Vertical Acceleration

At least two vertically oriented accelerometers should be recorded for drop test fixtures that employ two or more guide rails to maintain a level test platform during free fall. A vertical accelerometer (z1) should be placed on the test platform at the base of the seat at a rigid location as close as possible to the load path. The second vertical accelerometer (z3) should be placed on the seat cushion (i.e., the seat pad) between the cushion and the inert payload as close as possible to the vertical axis of seat motion.

> *Tip: Seat pad accelerometers are commercially available from several manufacturers to measure response motions on the seat cushion.*

Horizontal Acceleration

For drop test fixtures that do not have vertical guide rails, tri-axial accelerometers should be positioned on the test platform below the spring-damper assembly and on the seat cushion. The recorded horizontal accelerations (i.e., X1, Y1, X2, and Y2 in Figure 3) are used to ensure the test platform remains horizontal during the test.

Pan Acceleration

An optional vertical accelerometer may be installed at a rigid location on the seat pan as close as possible to the load path (i.e., beneath the seat above the spring damper assembly). A comparison of the pan acceleration and the cushion acceleration provides an assessment of the effects of the seat cushion material. Appendix D summarizes lessons learned related to seat cushion comfort and protection in a dynamic environment.

Relative Displacement

Optional sensors for measuring relative displacement across the spring-damper assembly include linear and string potentiometers, and electro-optical and laser rangefinders. The linear displacement sensor (if used) should have a nominal full-scale range of 24 inches, minimum accuracy of 2 percent, and a nominal repeatability of 0.1 percent.

TEST SEVERITY THRESHOLD

Pulse Shape

The test severity threshold defines the required shape, amplitude, and duration of the vertical acceleration applied to the base of the seat to be a valid test. The ideal test pulse is a vertical rigid body acceleration curve with a half-sine shape.

Pulse Amplitude and Duration

The peak vertical acceleration defines the threshold pulse amplitude. Six peak acceleration thresholds are listed in Table 1. These severity levels simulate impacts for a broad range of operational profiles for different types of planing craft[4]. The recorded half-sine pulse amplitude should fall within tolerances described below. All craft do not require seats capable of effective performance at Level 6 severity. Appendix E provides guidance for specifying drop test severity for different classes of craft based on generic operational profiles. The ideal pulse duration is 0.10 seconds. The pulse duration tolerances are listed in Table 2. A digital time history in ASCII format should be included in the impact test report to verify test results. Figure 4 shows an example half-sine pulse for a Level 5 severity threshold[5]. The curve was generated by adding zeroes to the beginning of the pulse from time zero to time 0.4T. Data points with amplitude zero were added after the pulse to 1.0 second. In the actual test data there will be residual movement after the impact pulse.

[4] This information is contained in a limited distribution U.S. Navy report.
[5] UERDTools was used to create all plots in this report [10].

Table 1. Test Severity Thresholds

Threshold Level	Drop Test Severity Threshold		
	Peak Acceleration		Nominal Impact Duration
	m/sec^2	g	sec
6	100	10.19	0.10
5	80	8.15	0.10
4	60	6.12	0.10
3	50	5.09	0.10
2	40	4.08	0.10
1	30	3.05	0.10

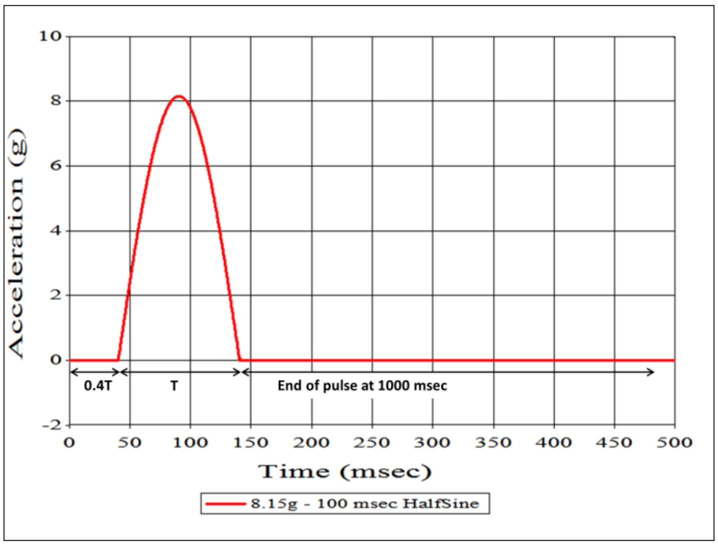

Figure 4. Example half-sine pulse: Level 5, 100 msec

Test Severity Tolerance

Vertical Acceleration Tolerance

The recorded vertical acceleration at the base of the seat must fall within tolerance criteria of the threshold pulse to be a valid test. Table 2 lists the tolerances of the allowable envelope for the vertical acceleration recorded at the base of the seat, where (A) is the peak acceleration (low-pass filtered to 20 Hz using a Butterworth filter). These tolerances should be used for drop test methods and alternative tests.

Table 2. Coordinates for Vertical Acceleration Tolerances

Time (seconds)	Acceleration (g)	
	Lower Bound	Upper Bound
-0.15	-1.1	-0.9
-0.06		-0.5
-0.03	-1.1	
-0.015		1.2 A
0	A	
0.015		1.2 A
0.04	-2	
0.05		0.6 A
0.15	-2	
0.5	-0.1	0.1
0.6	-0.1	0.1

Figure 5 shows the tolerance envelopes from Table 2 constructed around the Level 5 acceleration threshold. The larger envelope tolerances from approximately 0.05 seconds to 0.3 seconds are intended to envelope the seat base movement that will occur due to spring-damper oscillations after the impact. Appendix F shows the tolerance envelopes for the six severity threshold levels.

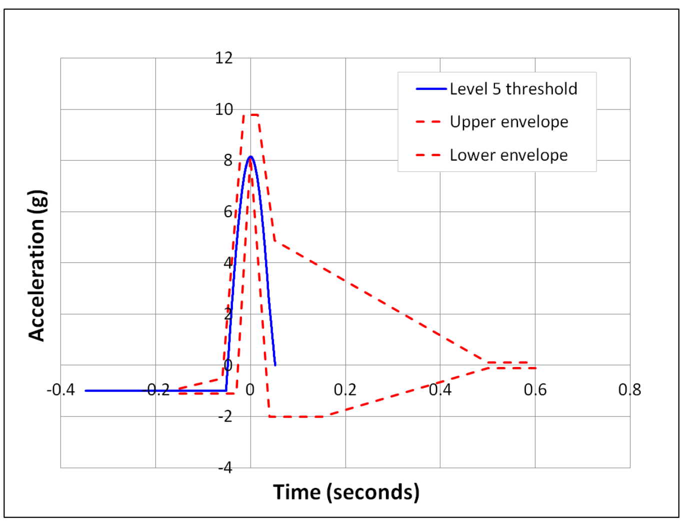

Figure 5. Example envelopes with the Level 5 threshold acceleration

Horizontal Acceleration Tolerances for Drop Tests

Horizontal tolerances apply to drop test fixtures that do not employ guide rails. The purpose of horizontal measurements is to ensure that the test platform is relatively horizontal

before and after impact [2]. The magnitudes of accelerations in the horizontal x and y directions should fit within the tolerance envelope listed in Table 3. Figure 6 shows an example plot of the horizontal acceleration envelopes.

Table 3. Coordinates for Horizontal Acceleration Envelopes

Time	Acceleration (g)	
(seconds)	Upper envelope	Lower envelope
-0.2	0.2	-0.2
-0.1	0.2	-0.2
-0.09	2	-2
0.49	2	-2
0.5	1	-1
1	0.2	-0.2
1.5	0.2	-0.2

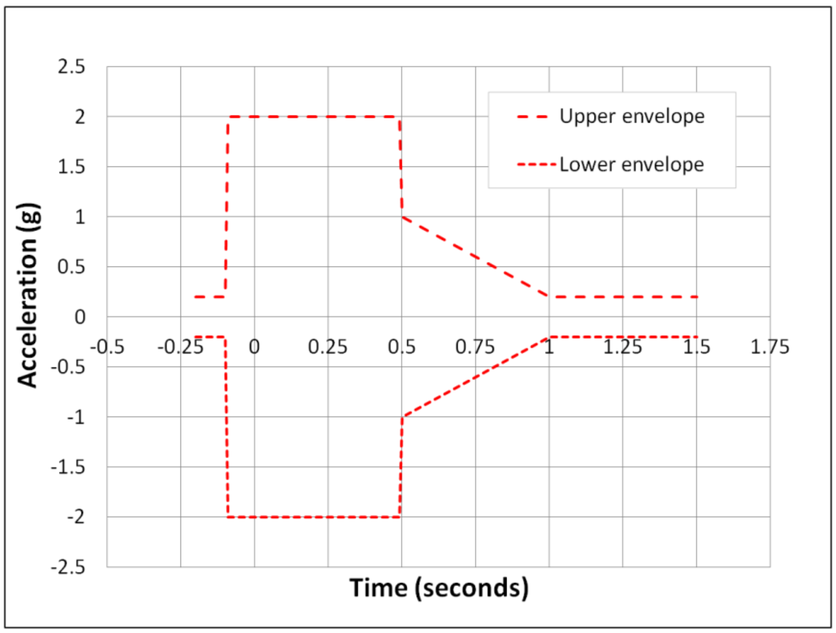

Figure 6. Horizontal acceleration envelopes

TEST PROCEDURE

Test Specification

This initial report is a guide that can be referenced by procurement documents if a test specification is also cited. The test specification should include the following: the maximum test severity threshold to be achieved during the sequence of tests (see Appendix E), the payload weights to be tested (nominally 2 or 3, see Appendix A), and the total number of tests to be performed (nominally three tests for each payload weight). If different from guidance presented herein, the test specification should also include seat operational requirements, protection requirements or goals in terms of mitigation ratios, failure criteria, sensor locations, and test report content.

Test Sequence

A test sequence is a series of drop tests for one payload weight. The test sequence for each payload weight should start with drop tests at Level 1 and proceed through the successive higher levels up to the most severe level specified. Each level of valid testing should be repeated three times. A valid test is achieved when the 20-Hz low-pass filtered acceleration curve for the seat base accelerometer falls within the tolerance envelopes.

Seat Configuration

Seats with manual adjustments for changing stiffness or damping characteristics should be set or configured for the payload weight being tested. Manual adjustments should not be made during a sequence of tests.

Test Completion

Maximum Threshold Achieved

A test sequence for a given payload is completed when 3 valid tests have been conducted at all threshold levels up to the specified maximum threshold level.

Exceeding Failure Criteria

The test sequence for a given payload is completed if a failure criterion is exceeded. The mitigation ratio criterion is exceeded when the computed MR is greater than or equal to 1.0 (see Appendix B). In some instances a mild bottom impact may result in a mitigation ratio less than 1.0. Testing after a mild bottom impact with MR less than 1.0 may be continued at the discretion of the test director to evaluate repeatability of the mild bottom impact or to evaluate seat performance at the next higher threshold level. Continued testing after a severe bottom impact is not recommended because the mitigation ratio will likely have exceeded 1.0.

All Payloads Tested

A testing program is completed when all specified payload weights and severity thresholds have been tested.

DATA PROCESSING

Vertical Zero Axis

The zero axes for all recorded vertical acceleration data should be calibrated so that zero means at rest and -1 g corresponds to acceleration due to earth's gravity (i.e., free-fall).

Low-pass Filter

All recorded acceleration data should be post-processed using a low-pass 4-pole Butterworth filter with a 20-Hz cut-off frequency [11, 12]. Time history plots of low-pass filtered acceleration data recorded at the seat base (with tolerance envelopes) and on the seat cushion should be included in the test report. Other data plots may be provided as appropriate.

Mitigation Ratio

The mitigation ratio (MR) should be computed using the 20-Hz low-pass filtered acceleration data for each drop test. Appendix B summarizes how shock response spectra (SRS) are used to compute the ratio. The use of shock response spectra (SRS) is documented in ISO 18431-4: 2006E Mechanical vibration and shock – Signal Processing – Part 4. All results should be tabulated as shown in Table 4.

Table 4. Example Test Results: Severity Threshold Level 4[6]

78 Kilogram payload			
Drop test Number	Severity Threshold Level	Seat Base Peak Acceleration (g)	Mitigation Ratio
1	1	3.5	0.62
2	1	3.6	0.65
3	1	3.4	0.63
4	2	4.4	0.66
5	2	4.4	0.65
6	2	4.5	0.67
7	3	5.2	0.72
8	3	5.3	0.78
9	3	5.1	0.75
10	4	6.5	0.89
11	4	6.4	0.92
12	4	6.5	0.91

[6] Not actual drop test data

TEST REPORT

General Requirement

Unless otherwise specified, the test report should present text, photographs, sketches, acceleration data plots, and data tables that summarize test conduct and results.

Report Contents

The report should include, but not be limited to the following:

a. Seat manufacturer, model, description, manual adjustment positions (as tested if present)

b. Test date, test laboratory

c. Maximum threshold severity level

d. Payload weight(s), description, tie-down method

e. Instrumentation system and sensors

f. Description and photograph of seat/payload assembly on drop test fixture

g. Description of test execution sequence

h. Tabulated MR test results for all tests

i. Certification statement

Test Certification

Certification Statement

The following certification statement should be included in the test report. “I certify that these tests were conducted on a production line seat in accordance with NSWCCD-80-TR-2015/010, and that the test data presented are from actual tests.”

Certification Signature

The certification statement should be followed by the printed name, signature, and the signature date.

REFERENCES

1. Gannon, Dr. L., Smith, C., *Shock Mitigation Seat Single Impact Program*, Defense Research and Development Canada Atlantic, DRDC-RDDC-2014-C89, April 2014
2. *Maritime Whole Body Vibration, Shock Mitigating Seat Test Protocol 1*, PQQ Reference JK6KHJ8427, Ministry of Defense, Defense Equipment and Support Organization, United Kingdom, 1 August 2014.
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12. Riley, Michael R., Coats, Dr. Timothy W., *Quantifying Mitigation Characteristics of Shock Isolation Seats in a Wave Impact Environment*, Naval Surface Warfare Center Carderock Division Report NSWCCD-TR-80-2015/001, January 2015.

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APPENDIX A. PAYLOAD WEIGHT GUIDANCE

Reference A1 provides a variety of anthropometric measurements for service members. Since its publication a recent study by the U.S. Army Readiness Command reported a weight increase in the general male population between 1988 and 2007. Table A1 provides a list of updated estimates of 5th, 50th, and 95th percentile male and female weights based on the U.S. Army findings. These payload weights may be used unless weights for specific populations are specified.

Added weight of foul weather clothing or equipment worn by seat occupants should be added to Table A1 weights if specified.

Table A1. Interim Payload Weight Guidance

Population Percentile	Male		Female	
	lbs	kg	lbs	kg
95 th	248.6	112.8	195.3	88.6
50 th	184.0	83.5	145.2	65.9
5 th	135.8	61.6	109.3	49.6

Appendix A Reference

A1. DOD HDBK 743A, *Military Handbook Anthropometry of U.S. Military Personnel*, U.S. Department of Defense, 13 February 1991.

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APPENDIX B. SHOCK SEVERITY

Shock Response Spectrum

The shock response spectrum (SRS) is a universal mathematical tool used to quantify and compare the severity of different shock motions [B1 – B9]. Example applications include comparing field shock test data to laboratory test machine data to ensure laboratory tests simulate the severity of actual field conditions, or comparing field shock test data to draft shock design levels to ensure shock design criteria conservatively envelope actual field conditions. SRS are also used for evaluating how systematic changes in test parameters affect shock response severity. The SRS is therefore very useful for comparing the severity of a deck input shock motion to the severity of the response motion recorded on a seat cushion.

Before introducing the shock response spectrum, the following paragraphs present an example calculation to illustrate how a mathematical model of a single-degree-of-freedom system is used to evaluate and compare the severity of two different shock motions that have the same peak acceleration, but different durations, different changes in velocity, and different average values of jerk.

Figure B1 shows a model of a single-degree-of-freedom (SDOF) system. The system has a base attached to a mass (m) by a spring (with stiffness k) and a damper (with damping coefficient c). For a prescribed shock input motion X (t) at the base of the system the resulting response of the mass (m) is Y (t). The relative displacement Z (t) between the base and the mass is X (t) minus Y (t). The equation of motion of the system (i.e., equation B1) is obtained by summing the inertial force of the mass and the forces within the spring and damper [B2].

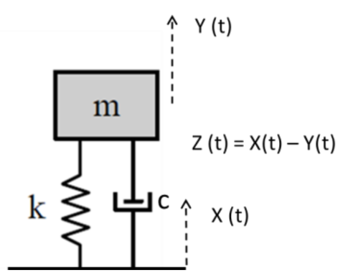

Figure B1. Single-degree-of-freedom Mathematical Model

$$m\,\ddot{y}(t) = -k\,z(t) - c\,\dot{z}(t) \qquad \text{Equation (B1)}$$

The damping factor, or damping ratio, is given by equation B2.

$$\xi = \frac{c}{2\,m\,\omega} \qquad \text{Equation (B2)}$$

The natural frequency (f) in Hertz (Hz) of the SDOF system is given by equation B3.

$$f = \frac{\omega}{2\pi} = \left(\frac{1}{2\pi}\right)\sqrt{\frac{k}{m}} \text{ Hz} \qquad \text{Equation (B3)}$$

The solution of equation (B1) provides the predicted response motion of the mass (m) caused by the base input motion either in terms of the absolute motion of the mass Y(t) or the relative motion Z(t) between the base and the mass. Mathematical solutions to equation (B1) for different pulse shapes are presented in reference B2.

The maximum predicted acceleration response of the SDOF mass (m) is a useful measure for comparing shock severity because it is proportional to the maximum inertial force (i.e., shock force) acting on the mass as a result of the shock input. Likewise, the maximum predicted relative displacement across the SDOF spring is a useful measure because it is proportional to the maximum strain in the spring. Both maximum values (i.e., peak acceleration response and maximum relative displacement) are a measure of the severity of the shock input (in terms of shock force acting on the mass and strain in the spring). When two different shock pulses are being compared, the one that results in the larger maximum acceleration and larger relative displacement in the SDOF model is the more severe shock pulse. This is illustrated further in the following paragraphs.

The left plot in Figure B2 shows the two hypothetical shock pulses with the same 8-g peak acceleration arbitrarily denoted shock input A and B. Shock pulse B has the longer duration (175 msec versus 100 msec). For the purpose of the mathematical comparison a SDOF mathematical model with a 9% damping ratio and a natural frequency of 13.5 Hz is arbitrarily selected to evaluate severity in the response domain. The plot on the right in Figure B2 shows the predicted absolute acceleration responses of the mass (m) caused by shock pulse A and shock pulse B. The peak acceleration response for pulse A is predicted to be 11.39 g and the peak response for pulse B is 8.46 g. These values along with the predicted maximum relative displacements for the SDOF system are listed in Table B1. The predicted maximum relative displacement for pulse A is 0.015 millimeters and for pulse B it is 0.011 millimeters. These results in the response domain indicate that pulse A is predicted to result in a larger peak acceleration response and a larger maximum relative displacement, thus pulse A is more severe than shock pulse B for a 13.5-Hz SDOF system.

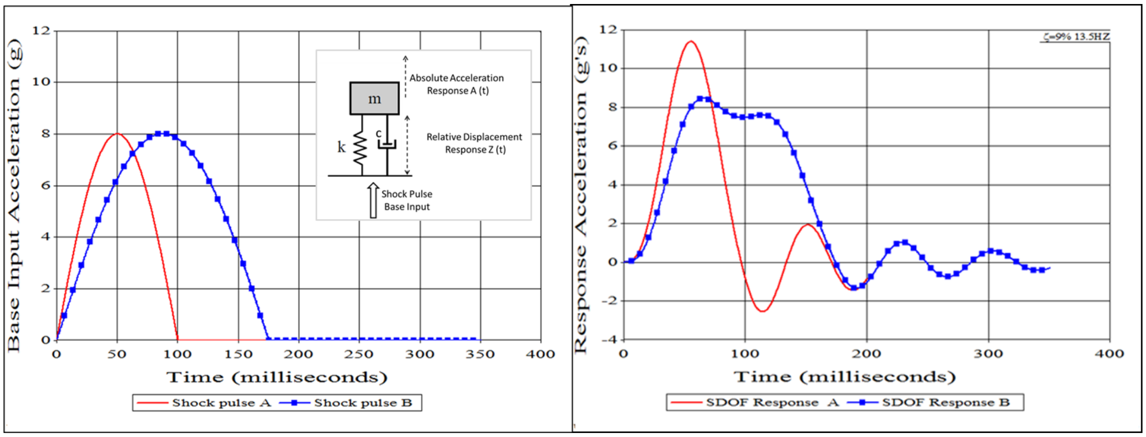

Figure B2. 13.5-Hz SDOF System Input and Predicted Response Accelerations

In this example the 13.5-Hz SDOF system was chosen arbitrarily to illustrate the comparison. When many other calculations are made for other values of SDOF system natural frequency, the plot of the maximum response (either peak acceleration response or maximum relative displacement) for a given shock input versus system natural frequency is referred to as a shock response spectrum. It is a plot of SDOF system maximum shock response versus SDOF model natural frequency. The following examples illustrate the shock response spectrum concept.

Table B1. 13.5-Hz SDOF System Maximum Responses

Shock Pulse Input	13.5 Hz System Response			
	Response A_{MAX}		Response Z_{MAX}	
	m/sec^2	g	mm	inch
A	111.736	11.390	0.015	0.606
B	82.993	8.460	0.011	0.449

The acceleration plots in Figure B3 show predicted response motions (i.e., acceleration versus time) for a 30-Hz SDOF system (red circles) and a 5-Hz SDOF system (blue triangles). The shock input motion for each prediction was assumed to be a half-sine acceleration pulse with a peak of 10 g and 50-millisecond duration (black curve). The maximum response acceleration predicted for the 30-Hz system is 13.6 g. The maximum response predicted for the 5-Hz system is 8.2 g. Thus it is observed that the maximum response (i.e., peak acceleration in this example) of the SDOF system is a function of the natural frequency (f) of the SDOF model.

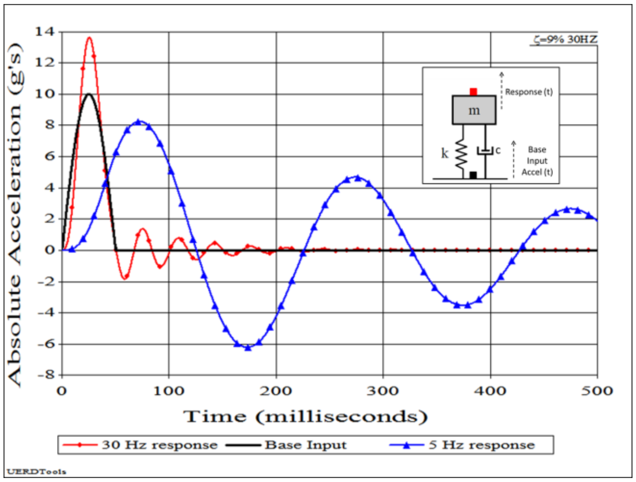

Figure B3. SDOF Model with Sample Base Input and Predicted Responses

Figure B4 presents a plot of the maximum acceleration response of the SDOF model for model natural frequencies from 4 Hz to 80 Hz for the 10 g – 50 msec base input pulse. It is called an acceleration shock response spectrum (ASRS). The symbols in the figure identify the two predicted peak response values shown in Figure B3 (i.e., 13.6 g for 30 Hz and 8.2 g for 5 Hz).

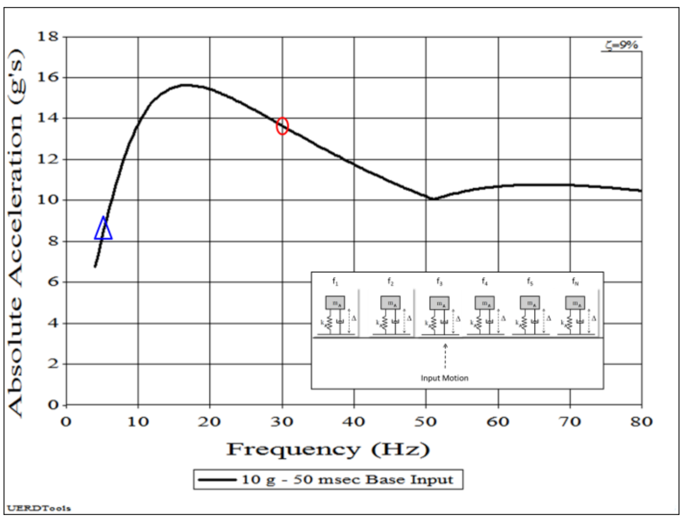

Figure B4. Acceleration SRS for 10g-50 msec Base Input

The maximum response of the SDOF system can also be plotted as a function of the maximum relative displacement (Z_{MAX}) across the SDOF model's spring. Figure B5 shows a plot of the maximum relative displacement caused by the 10 g -50 msec base input acceleration (half sine) as a function of model natural frequency. It is called a relative displacement SRS (DSRS).

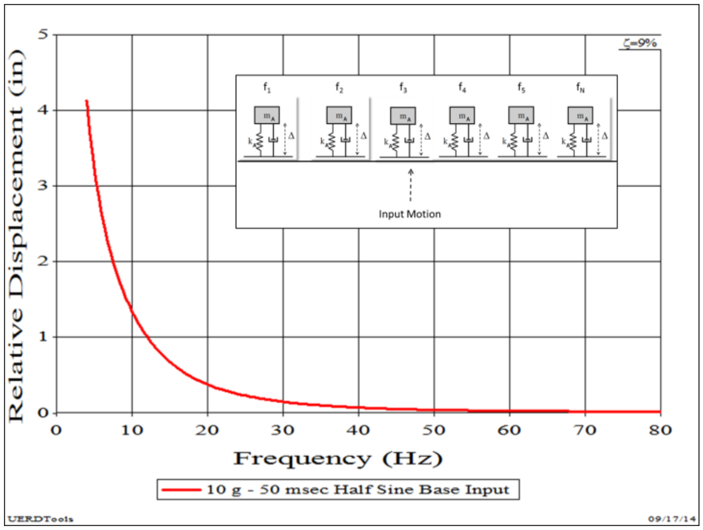

Figure B5. Maximum Relative Displacement SRS

The maximum acceleration and the maximum relative displacement values from Figures B4 and B5 can be combined into a convenient four-coordinate plot referred to as a pseudo-velocity shock response spectrum (PVSRS) as shown in Figure B6. Logarithmic scales are used on all four axes. The horizontal lines are the pseudo-velocity scale. Vertical lines are the system natural frequency scale. Lines sloping down to the left show the predicted maximum relative displacement scale and lines sloping down to the right show the predicted maximum response acceleration scale. The PVSRS provides a measure of the shock severity in units of displacement, velocity, and acceleration. The acceleration scale is sometimes referred to as the pseudo-acceleration for damped systems if the acceleration values are calculated using equation (B2), which applies for lightly damped or zero damped systems.

$$A_{MAX} = (2\pi f)^2 \Delta_{MAX} \qquad \text{Equation (B4)}$$

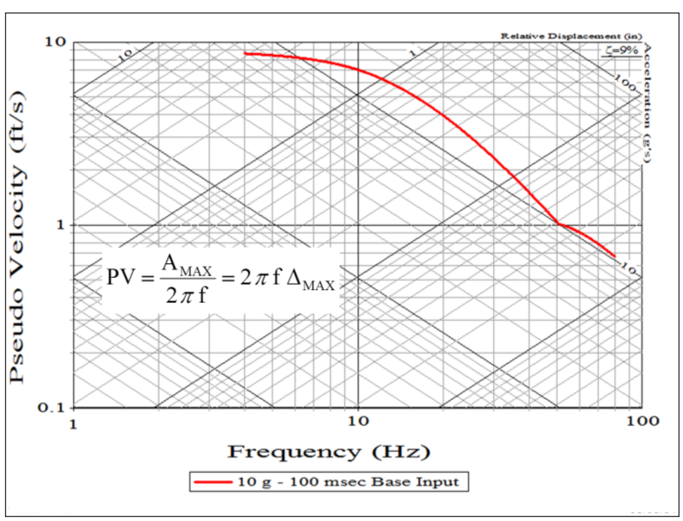

Figure B6. Pseudo-Velocity SRS

Mitigation Ratio Using SRS

The seat mitigation ratio using SRS is the ratio of the seat cushion shock response spectrum (SRS_S) divided by the seat base shock response spectrum (SRS_B) .

$$\text{Mitigation Ratio} = \frac{SRS_S}{SRS_B} \qquad \text{Equation B5}$$

If the ratio is greater than 1.0, the shock pulse for the seat is more severe than the shock pulse for the base input. If the ratio is less than 1.0, the shock pulse for the seat is less severe than the shock pulse for the base input. As an example, Figure B7 shows relative displacement SRS (DSRS) for two hypothetical half-sine pulses: a 7 g – 100 msec base input acceleration and a 5 g – 210 msec seat response acceleration. The question is how much less severe or more severe is the seat response pulse compared to the base input pulse?

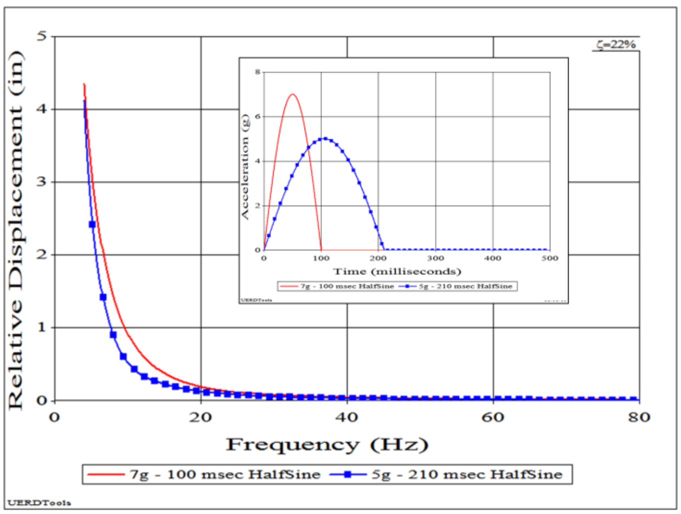

Figure B7. Comparison of Hypothetical DSRS

To answer this question Figure B8 was constructed by dividing the DSRS for the 5 g – 210 msec pulse by the DSRS for the 7 g – 100 msec pulse. A damping ratio of 22 percent was assumed for the calculations. It shows that over a broad frequency range the 5 g – 210 msec shock pulse is less severe than the 7 g – 100 msec pulse (i.e., the ratio is less than 1.0). For natural frequencies greater than approximately 30 Hz the mitigation ratio is approximately 0.70 (i.e., the 5-g pulse is 30 percent less severe than the 7-g pulse). Between 4 Hz and 30 Hz the mitigation ratio varies from 0.55 to 0.7 (i.e., 30 percent to 45 percent less severe).

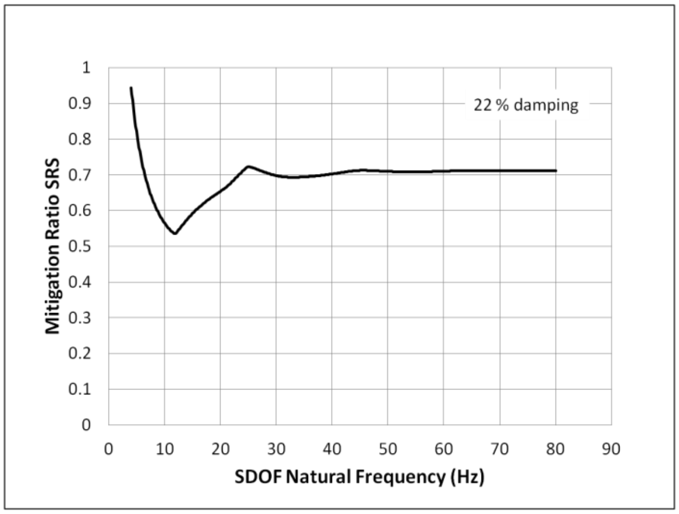

Figure B8. Mitigation Ratio for 5 g and 7 g Half-sine Pulses

The mitigation ratio based on relative displacement shock response spectra (DSRS) is a convenient relative measure of shock input severity because (1) it takes into account the effects of acceleration magnitude, pulse duration, and the rate of acceleration application (i.e., jerk), and (2) because of its relationship to compressive strain or stress in the SDOF mathematical model [B10]. The concept of stress as a measure of shock severity is not new. The early NASA studies concluded that magnitude (i.e., peak acceleration) alone does not define shock severity, nor does acceleration cause damage in a system. Stress (or strain), a result of acceleration, causes damage [B11]. Methods that account for acceleration amplitude, duration, and relative displacement were considered superior for assessing severe shock effects on humans [B12]. The comparison of displacement shock response spectra is therefore a convenient measure for comparing the relative severity between the seat base input and seat cushion shock pulses.

Seat Comparison Criteria

Selection of the frequency value of interest and the SRS damping ratio for the mitigation ratio calculation is based on the assumption that there is no intent to specifically model the item being subjected to the shock. The mathematical model of the SDOF system in this application is simply a mathematical ruler for relative comparisons of shock intensity. But the ruler can be made more relevant for the investigation by considering the frequency (or frequencies) and damping characteristics of interest. If very stiff items are being subjected to shock then the frequency of interest may be 50 Hz to 70 Hz or more. If the item being subjected to shock is more flexible a frequency less than 15 Hz may be more relevant for the mathematical ruler. The intent is not to model the item being subjected to the shock, but rather to select a relevant frequency that renders the mathematical ruler (i.e., the mitigation ratio) more meaningful for the application.

As an example, the occupant of a shock mitigation seat is not a stiff 80-Hz system like an aluminum truss structure. Therefore the mitigation ratio for an 80-Hz SDOF model would be less relevant than a lower frequency. Previous investigations involving lifeboat drop tests recommend that a SDOF system with an 8- Hz natural frequency and 22% damping is relevant when

evaluating single impacts for seat occupants [B12]. The recommended criteria for calculating the mitigation ratio (i.e., the mathematical ruler) for shock isolation seat test data is therefore 8 Hz and 22% damping. The intent is not to model a seat occupant, but rather to render the mathematical SDOF ruler more relevant to evaluating shock isolation seat performance. An example calculation is presented in the next paragraph.

The upper curve in Figure B9 shows the 20-Hz low-pass filtered acceleration pulses for a single wave impact recorded during craft seakeeping trials. The black curve was recorded at the base of a shock isolation seat and the red curve with triangle symbols was recorded on the seat cushion below the seat payload. The lower plot shows the calculated 22% damped relative-displacement spectra for the two pulses. For a natural frequency of 8 Hz the mitigation ratio is 0.28 inches for the seat base divided by 0.40 inches for the seat cushion, or 0.70. In other words, the spring-damper-cushion assembly reduced the seat base input severity by approximately 30-percent.

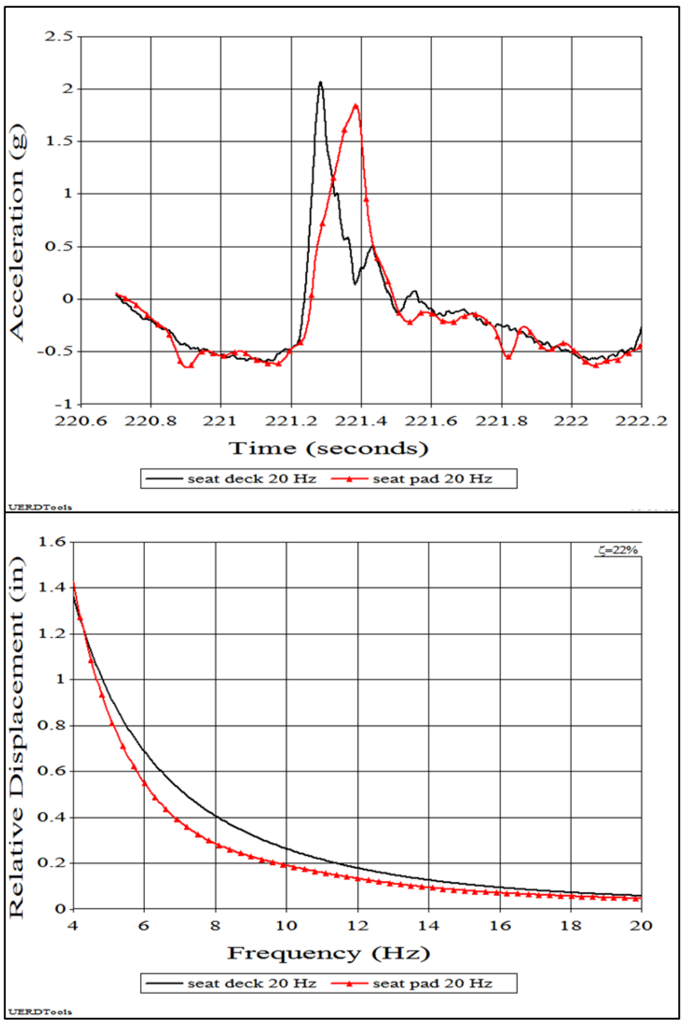

Figure B9. Recorded Seat Acceleration Data

Appendix B References

B1. ANSI/ASA S2.62-2009, *Shock Test Requirements for Equipment in a Rugged Shock Environment*, American National Standards Institute, Acoustical Society of America, Melville, N.Y., 9 June 2009.

B2. Harris, Cecil M., editor-in-chief, *Shock and Vibration Handbook*, Fourth Edition, McGraw-Hill Companies, Inc., New York, New York, 1995.

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B4. ASTM D5487:2008, *Standard Test Method for Simulated Drop of Loaded Containers by Shock Machines*, American Society of Testing and Materials, West Conshohocken, Pennsylvania, April 2008.

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B9. ISO-18431-4: 2007, *Mechanical vibration and shock – Signal processing – Part 4: Shock response spectrum analysis*, International Organization for Standardization, Geneva, Switzerland, 2007.

B10. Riley, Michael R., Coats, Dr. Timothy W., *Quantifying Mitigation Characteristics of Shock Isolation Seats in a Wave Impact Environment*, Naval Surface Warfare Center Carderock Division Report NSWCCD-TR-80-2015/001, January 2015.

B11. Eiband, Martin A., *Human Tolerance to Rapidly Applied Accelerations: A Summary of the Literature*, Lewis Research Center, National Aeronautics and Space Administration, Memorandum 5-19-59E, Cleveland, Ohio, June 1959.

B12. Gollwitzer, Richard M., Peterson, Ronald S., *Repeated Water Entry Shocks on High-Speed Boats*, Dahlgren Division Naval Surface Warfare Center, Panama City Report CSS/TR-96/27, September 1995.

B13. *Testing and Evaluation of Life-Saving Appliances*, Maritime Safety Committee Resolution MSC.81(70), Life-Saving Appliances, 2003 Edition, International Maritime Organization, 2003.

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APPENDIX C. WEDGE TEST FIXTURE

Wedge Description

Figure C1 shows a wedge test fixture used to achieve nominal 100-msec half-sine pulses. The dimensions of the wedge are shown in Figure C2. All dimensions are in millimeters. The wedge was constructed using 6mm thick steel plate and was attached to the base of the test platform. The apex of the wedge was formed from a piano hinge.

The test platform consisted of mild steel plates with a combined thickness of approximately 60mm and dimensions of 510mm x 510mm.

The wedge was dropped into sand held in place by a box with dimensions of 0.82m x 0.82m x 0.5m. The sand box was filled with dry sand to a depth of at least 0.36m. The sand was levelled prior to each test.

Figure C1. Test Platform including Wedge End View[C1]

[C1] United Kingdom Crown copyright photograph with permission

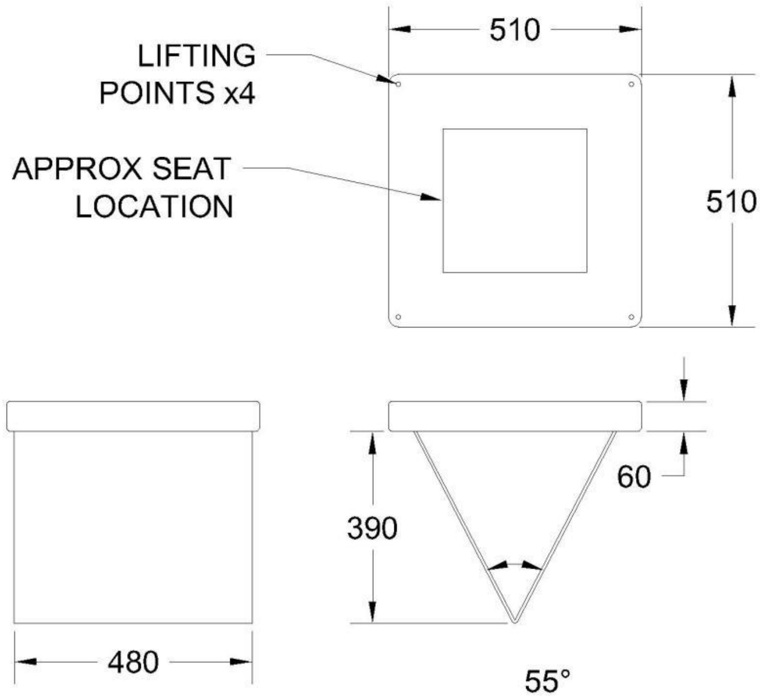

Figure C2 Dimensions of Test Platform and Wedge (all dimensions in mm)[C2]

[C2] United Kingdom Crown copyright drawing with permission

APPENDIX D. SEAT CUSHION DYNAMICS

Acceleration data recorded during seakeeping trials of high-speed planing craft demonstrates that the same lessons learned in the aviation industry for airplane ejection and crash impacts also apply for wave impacts [D1, D2]. The lessons are summarized below.

The compliance of soft seat cushion material results in relative displacements between the seat pan and the top of the cushion that can cause load amplification in a severe wave impact environment. The total change in impulse will be the same for cushioned seat or hard seat conditions, but a higher load will be applied for a shorter period of time on a soft cushion. The selection of seat cushion materials is therefore a compromise between soft-compliant materials that provide comfort and harder seat materials that prevent or limit impact load amplification.

Seat cushions are primarily designed for comfort. Their form fitting characteristic spreads the occupant load over the largest possible area in non-impact environments thereby decreasing high pressure points and preventing restriction of blood flow.

Every effort should be made to design a cushion that acts as a shock damper between the occupant and the mass of the seat and minimizes relative motion between the occupant and the seat. Otherwise impact force (or acceleration) amplification can occur.

Relative motions can be minimized by increased foam density and/or reduced foam thickness.

Different layers of viscoelastic and loading-rate-sensitive materials can be used to achieve these goals.

Cushion comfort is of primary concern and must not be unduly compromised to achieve crash (i.e., impact) safety.

Appendix D References

D1. Olivares, Dr. Gerardo, *Dynamic Seat Certification by Analysis: Volume III – Comparison of Hybrid II versus Hybrid III ATD Dynamic Evaluation NIAR Test Series*, NIAR Technical Report FAA-003D, Wichita, KS, September 2009.

D2. Riley, Michael R., Murphy, Heidi, Coats, Dr. Timothy, *Initial Investigation of Wave Impact Load Transfer Through Shock Mitigation Seats in High-Speed Planing Craft*, Naval Surface Warfare Center Carderock Division Report NSWCCD-23-TM-2013/35, August 2013.

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APPENDIX E. TEST SEVERITY GUIDANCE

Four suggested craft classifications provide a framework for specifying test severities for shock isolation seats [E1]: Class 1 Low Speed Commercial/Leisure, Class 2 High Speed Commercial / Leisure, Class 3 Search and Rescue, and Class 4 Military. This class rating scale was developed from experience of trials on commercial, leisure, search and rescue, and military rigid hull inflatable boats in the UK with vessel lengths from 5 to 10 meters. Generic descriptions of Class 1, 2, 3, and 4 are provided below.

Class 1: Low Speed Commercial / Leisure

Class 1 describes small high speed craft carrying passengers of various ages and physical conditions, possibly including children and the elderly. Typical applications include ferry craft and sightseeing tours. Class 1 craft will typically operate at low speeds except in extremely calm conditions. Wave impacts are avoided. Class 1 vessels generally do not operate in poor weather. Class 1 corresponds to craft with operational environments not typically requiring personnel protection in the form of shock isolation seats.

Class 2: High Speed Commercial / Leisure

Class 2 describes small high speed craft similar to Class 1 vessels, where the Class 2 vessel operator may choose to operate at higher speeds, as limited by their own tolerance.

Typical applications include commercial operators offering *thrill rides* and marine wildlife tour boats that are capable of high speed transits. Some applications, such as maritime wind farm maintenance boats, may require operations in poor weather. Crew and passengers of Class 2 vessels are often required to meet physical fitness standards. Engines on Class 2 vessels are typically more powerful than on Class 1 vessels, and so speeds are typically higher, perhaps in excess of 20 knots when conditions allow. Wave impacts are more common on Class 2 vessels than on Class 1 vessels.

Class 3: Search and Rescue

Class 3 describes small high speed craft used for search and rescue (SAR), which often requires operations at high speed in poor weather, and in relatively high sea states. Class 3 vessel personnel are highly motivated, and well trained. They are experienced at operating in severe conditions, and are generally physically fit and healthy. Engines on Class 3 vessels often provide sufficient power to exceed 30 knots when conditions allow. Severe wave impact slamming events are typical for normal operation on Class 3 vessels.

Class 4: Military

Class 4 describes high-speed craft used for military operations. Personnel in Class 4 vessels are usually physically fit and very highly motivated. As a result of their training and experience

they are more accustomed to sustained, extreme motions and wave impacts during high-speed operations.

Table E1 lists suggested test levels for classes 2, 3, and 4 if not otherwise specified. The upper box of each gray shaded region in the table corresponds to the suggested maximum test severity for each class. Three levels for Military Class 4 are provided for acquisition program flexibility[E1].

The class definitions identify broad applications across leisure, commercial, and military craft where there is potential for operating in successively more severe wave impact environments. It is understood that the definitions may or may not fit a specific commercial, search and rescue, or military craft. It is therefore important that craft owners, program managers, or operators develop seat test requirements that identify the maximum exposure severity for specific craft applications.

Table E1. Recommended Testing Levels for Military and Commercial Craft

Test Severity						**Craft Class**				
Threshold Level	**Peak Acceleration**		**Nominal Impact Duration**	**Nominal Drop Height**		**Class 4**			**Class 3**	**Class 2**
	m/sec^2	g	sec	m	ft	**Military 4-3**	**Military 4-2**	**Military 4-1**	**Search and Rescue**	**High Speed Commercial or Leisure**
6	100	10.19	0.10	2.07	6.78	░				
5	80	8.15	0.10	1.32	4.34	░	░			
4	60	6.12	0.10	0.74	2.44	░	░	░	░	
3	50	5.09	0.10	0.51	1.69	░	░	░	░	░
2	40	4.08	0.10	0.33	1.08	░	░	░	░	░
1	30	3.05	0.10	0.18	0.61	░	░	░	░	░

Actual drop test heights needed to achieve acceleration thresholds will be different from the nominal drop heights listed in Table E1. The values listed are for inital calibration testing.

Appendix E References

E1. Colwell, J.L., Gannon, L., Gunston, T., Langlois, R.G., Riley, M.R., Coats, T.W., *Shock Mitigation Seat Test and Evaluation,* The Royal Institute of Naval Architects, 2011-288.

[E1] Further guidance provided in a limited distribution U. S. Navy report.

APPENDIX F. THRESHOLD LEVEL TOLERANCE ENVELOPES

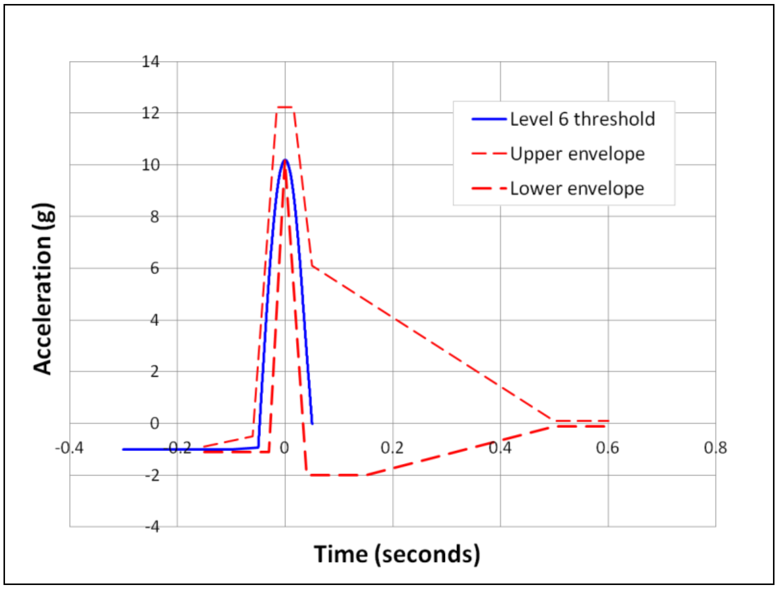

Figure F1. Level 6 Threshold and Tolerance Envelopes

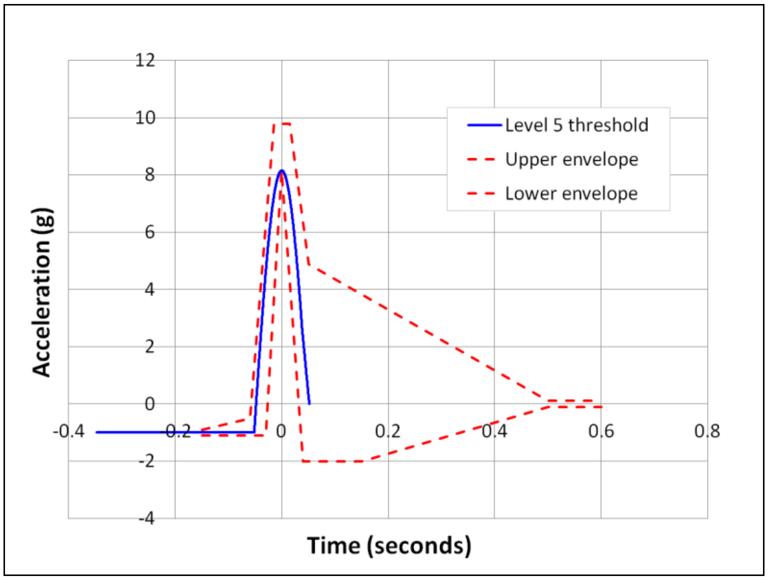

Figure F2. Level 5 Threshold and Tolerance Envelopes

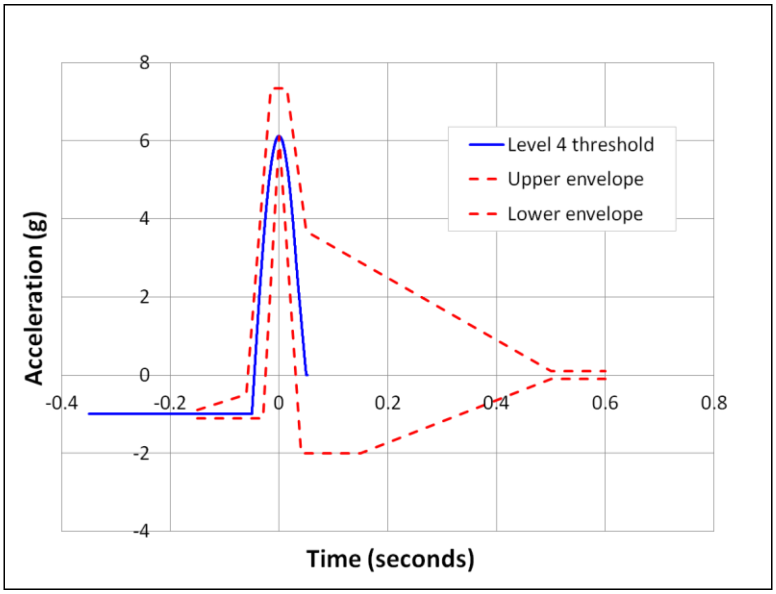

Figure F3. Level 4 Threshold and Tolerance Envelopes

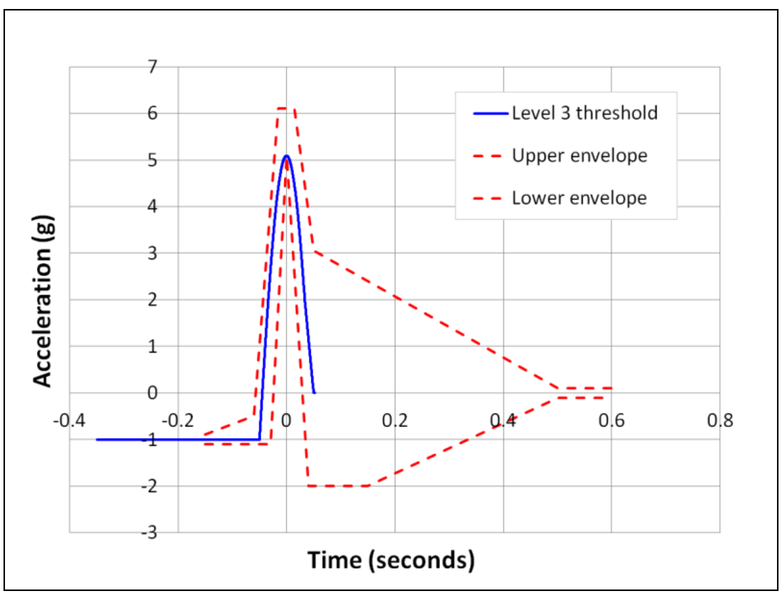

Figure F4. Level 3 Threshold and Tolerance Envelopes

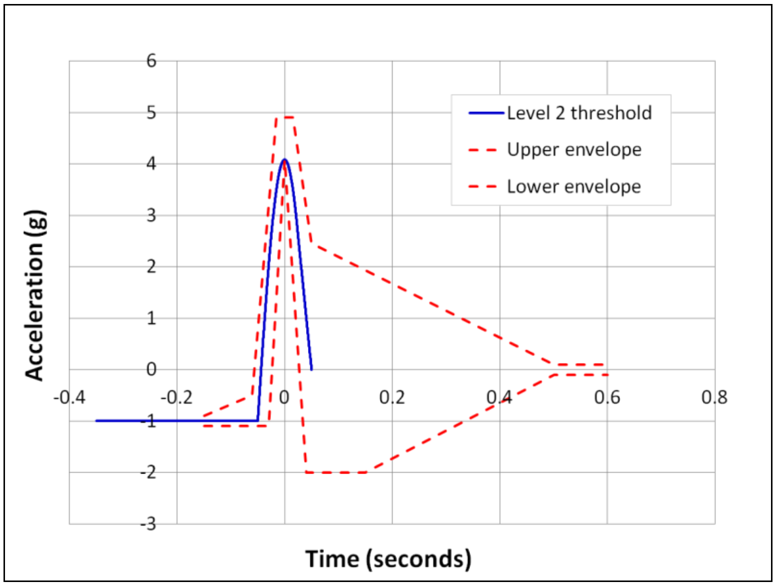

Figure F5. Level 2 Threshold and Tolerance Envelopes

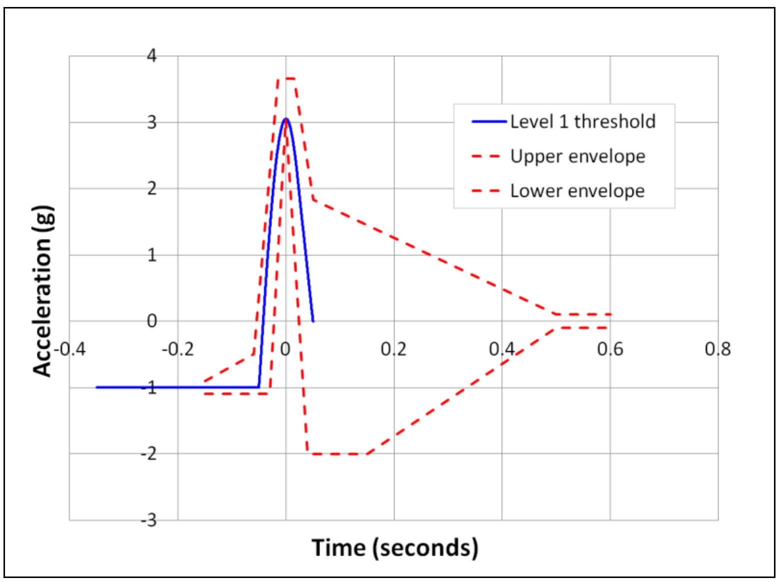

Figure F6. Level 1 Threshold and Tolerance Envelopes

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